# Deconfinement energy threshold: analysis of hadron yields at 11.6 $A$ GeV

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We analyze the hadron yields obtained at the AGS in the range 11–11.6 $A$ GeV and discuss strategies to identify possible deconfinement at this energy scale. These include consideration of chemical non-equilibrium at hadronization, and the study of (multi)strange hadrons. We find that the totality of experimental results available favors the interpretation as hadron freeze-out at the phase boundary between confined and deconfined phase.

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One of the most interesting issues, in the field of relativistic heavy ion collisions, is the understanding of the thresholds in reaction energy, and system size, beyond which the formation of the color deconfined partonic state occurs dominantly. In the central collisions of Au–Au ions at BNL–RHIC, at the top energy range ($\sqrt{s_{\rm NN}} = 200$ GeV), it is generally believed that a color deconfined state has been formed [1]. The strange antibaryon production systematics lead us to believe that this is also the case at the top energy in central Pb–Pb ion reactions at $\sqrt{s_{\rm NN}} = 17.2$ GeV (158 $A$ GeV/c Pb beam colliding with fixed target) at CERN–SPS [2]. Experimental exploration of lower energy collisions at SPS down to $\sqrt{s_{\rm NN}} = 6.3$ GeV (20 $A$ GeV/c) suggests a possible change in strangeness production pattern [3, 4]. In this analysis, we address the experimental program at BNL–AGS at $\sqrt{s_{\rm NN}} = 4.8$ GeV (11.6 $A$ GeV/c). Our objective is to apply the methods we used in the study of the SPS and RHIC data in order to identify similarities and differences in the hadron production pattern.

The tool used in this study of hadron production is the Statistical Hadronization (SH) model introduced by Fermi in 1950 [5]. In 50 years, SH has matured to a full fledged tool, in the study of soft strongly interacting particle production, capable to describe in detail hadron abundances once the statistical grand canonical method and the full spectrum of resonances is included [6]. The key SH parameters of interest are the temperature $T$ and the baryochemical potential $\mu_{\rm B}$. It is generally accepted that as the energy of the colliding nuclei varies, the properties of the hadronic gas (HG) and quark–gluon plasma phases (QGP) are explored in a wide domain of $T$ and $\mu_{\rm B}$ , see Fig. 2. in [7].

Two values of temperature can be determined in statistical hadronization studies: chemical freeze-out $T_{\rm ch}$, which determines particle abundances, and a thermal freeze-out $T_{\rm th}$, defined by the condition where the momentum spectra stop evolving, *i.e.*, particles stop interacting elastically. We analyze here solely the yields of hadronic and in particular strange particles and, hence from now, on we imply $T = T_{\rm ch}$. For $T$ to be uniquely determined for all particles considered the chemical freeze-out must occur rather fast. This requires that particles stop interacting just after formation (hadronization). In fact, the same freeze-out condition explains, at high energy SPS [2], and at RHIC [8], both particle abundances and spectra. This is the so called single freeze-out model expected to apply in presence of sudden hadronization of a rapidly expanding supercooled quark–gluon fireball [9].

The single freeze-out model, allowing for chemical non-equilibrium, is consistent with the observation by invariant mass method of abundantly produced hadron resonances by, *e.g.*, the STAR and NA49 collaborations [10, 11]. This results demonstrates that resonance decay products in essence have not scattered before their observation [24]. Hence resonance decay spectra contribute to the stable particle spectra, altering the purely thermal shape. An analysis of this modified shape yields the universal freeze-out condition [2, 8]. On the other hand, studies in which resonance decays are for simplicity ignored have as result a different thermal freeze-out condition for practically each particle considered, which differs from the chemical freeze-out condition obtained using hadron yields. These may serve as a comparison benchmark but cannot be used otherwise.

The question of chemical equilibration arises in the context of chemical freeze-out studies. The introduction, into the data analysis, of the strangeness phase space occupancy parameter $\gamma_s$ was motivated by the recognition that strangeness (or equivalently strange hadron) buildup in microscopic reactions will rarely lead to abundance expected in chemical equilibrium, $\gamma_s = 1$ [12]. The parameter $\gamma_s$ characterize, independently of temperature, the particle–antiparticle pair yield. Subsequently, the light quark phase space occupancy $\gamma_q$ was introduced [13]. This allowed to describe particle yields for the case of fast hadronization. Namely, the phase space density of quarks in QGP is very different from that obtained evaluating the yields of valance quark content in final state hadrons.

Thus, even if during its temporal evolution a QGP fireball converges to chemical equilibrium, the final hadron state generated on the scale of a few fm/c should emerge showing a pattern of subtle deviations from chemical

equilibrium which contain interesting information about the physics we are exploring [14, 15]. The claim that, in general, overall chemical equilibrium is reached in relativistic heavy ion collision is based on an analysis that presupposes this result [16]. In this paper, we show that while chemical equilibrium hypothesis for the 11 $A$ GeV reactions can be considered, the experimental results available today favor chemical under saturation of both light and strange quark phase spaces, with both $\gamma_s, \gamma_q < 1$.

Let us first explain how the different parameters of the SH model can be determined using the experimental data in a step by step process, rather than in a global fit, which erases much of the physics insight. We will show that it is possible to describe a partial subset of data with a partial subset of parameters since certain types of particle ratios are sensitive to subsets of statistical parameters. Of particular importance in this discussion is that the chemical non-equilibrium parameters $\gamma_s, \gamma_q$, require to be determined ratios of certain rarely produced particles.

a) The chemical fugacities $\lambda_q$, $\lambda_s$, see [12], and $\lambda_I$ (see e.g Eq. (1 below) can be determined rather precisely and independent of other statistical parameters considering the anti-particle to particle ratios. There are many such ratios available allowing to fix the three parameters, check consistency and to make ratio predictions based on a partial data set. Success of this part of SH model analysis has no predictive power regarding the value of the remaining 4 statistical parameters. Alas, we see again and again the argument to the contrary, in particular some workers claim based on the success of describing particle to antiparticle ratios that there is chemical equilibrium, $\gamma_s = \gamma_q = 1$, which is plainly wrong.

b) If one considers from that point on only the product of particle with antiparticle yield, to a very good approximation one obtains reduced yield ratios which are independent of $\lambda_q$, $\lambda_s$ and $\lambda_I$ . Than to determine the ratio $\gamma_s/\gamma_q$ (or equivalently $\gamma_s$ when $\gamma_q = 1$) we consider ratios of particles with unequal strangeness content, e.g. $\phi/\sqrt{\mathrm{K}^+\mathrm{K}^-} \propto \gamma_s/\gamma_q f_1(T)$ In such a ratio generally there is a correlation between $\gamma_s/\gamma_q$ and $T$ and thus at least two such ratios are required to determine $\gamma_s/\gamma_q$ and $T$, see for example Ref.[17], figure 4 .

c) Similarly, comparing yields of particles with different quark number content, e.g. mesons with baryons one identifies the value of $\gamma_q$, as noted in *e.g.*, Section IVD in Ref. [18]. Consider here as example $\Lambda\overline{\Lambda}/\mathrm{K}^+\mathrm{K}^- \propto \gamma_q f_2(T)$; we see that at least a second such ratio is required, e.g. $\sqrt{\Xi^-\overline{\Xi}^+}/\phi$ or/and $N\overline{N}/\pi^+\pi^-$ etc. to determine both $\gamma_q$ and $T$ or/and we take $T$ from the study of $\gamma_s/\gamma_q$ and $T$ above. We expressly did not introduce above pion yields as these derive from resonance decays including heavy baryons, and thus their yield is not strictly the yield of mesons. Moreover the pion yields are theoretically most uncertain considering possible extension of the hadron mass spectrum to higher mass, and uncertainties about number of pions produced in cascading decays of heavy resonances. In absence of experimental data regarding multistrange particles there is little choice but to compare the yields of pions to nucleons in the analysis of $\gamma_q$ and $T$.

d) Each individual total particle yield is proportional to the volume parameter $V$ aside of a strong dependence on $T$, and a lesser dependence on all the other SH parameters. This allows to fix $V$ and test the consistency of the individual findings about the other parameters made above.

In a more modern approach one makes a global and simultaneous fit of all parameters minimizing the global error ($\chi 2$). This can only work if there is sufficiently wide scope of experimental data as required in the individual steps above. Practical experience shows that an incomplete data set combined with the presence of a significant measurement error makes the task of unfolding $\gamma_s, \gamma_q$ and $T$ difficult. In this environment some workers think that it is better to assume $\gamma_q = 1$, we will discuss this at length below. Here we note that the predictive power of SH model can be tested: we can create choosing a set of SH model parameters a set of particle yields, and add in random errors. If the requirements on availability of measurements identified in a)–d) are respected in the data set considered, one can fit such an artificial data set to obtain the 'creating' set of statistical parameters. However, when large yield errors are introduced, and key particles eliminated, the expected solution will not always be found in the likelihood analysis.

Considering such studies it is important to remember that the SH model is not being verified or tested, its validity can be seen in its predictive power which encompasses particle yields that vary by typically four orders of magnitude, varying between $\mathcal{O}(\prime.\infty)$ and $\mathcal{O}(\infty\prime\prime)$. The issue before us is, *if and when* we can use statistical significance of the fit to infer the values of the parameters, and the insights obtained in such model studies are affirming this. For this reason it makes sense to look for most likely solutions using a full parameter set motivated by theoretical considerations.

The parameter $\gamma_q$ has been introduced into SH model not as a fit parameter, but in consequence of a theoretical development. It is the quantity which is expected to differ from unity considering hadron freeze-out from a rapidly expanding system and/or undergoing a sharp phase transformation. In such consideration $\gamma_q = 1$ only when there is a relatively long time available for chemical re-equilibration. Moreover, a large value of $\gamma_q$ allows the hadron gas phase to absorb without volume increase the enhanced entropy content of the deconfined phase in which color bonds are broken. The ability of the two models ($\gamma_q = 1$ and $\gamma_q \neq 1$) to describe data should be compared in a quantitative way in the study of statistical significance. Evidence for $\gamma_q > 1$ constitutes evidence for a rapidly evolving system emerging from a deconfined phase [19, 20].

Statistical significance [21], defined as the probability of the data fit to a model to be of the obtained quality,

provided that the model under consideration is 'true', and errors are purely due to experiment, is an appropriate tool for the comparison of model variants. This approach takes into account both the number of fit parameters and the 'goodness' ($\chi 2$) of the fit. In the absence of the experimental data necessary for strict falsification, it has been argued by others that a comparison of statistical significance is a more sound procedure than turning to a more restricted and less general model with the fewest number of fit parameters [22]. Specifically in our context, if the introduction of $\gamma_q$ as a fit parameter yields results expected from theoretical considerations, and at the same time this step raises statistical significance considerably, and furthermore makes the behavior of best fit parameters more consistent with expectation once experimental conditions are varied (collision energy and centrality [23]), than it is appropriate to conclude that current experimental data favor $\gamma_q \neq 1$.

The methods of SH analysis are described elsewhere in great detail. We refer the reader to SHARE (statistical hadronization with resonances), the public SH suit of (FORTRAN) programs which we use in this analysis [25]. The parameter set of SHARE comprises also the fugacity $\lambda_{\rm I}$, which describes the asymmetry in the yield of up $u$ and down $d$ valance quarks. This parameters cannot be omitted (tacitly set to unity) in the AGS physics environment, since the initial state isospin asymmetry is not diluted by a very large produced particle yield. To understand the relevance of $\lambda_{\rm I}$, note that, in Boltzmann approximation prior to resonance decays (subscript 'o'), we have for the pion ratio:

$$\frac{\pi_{\rm o}^+}{\pi_{\rm o}^-} = \lambda_{\rm I}^2 \equiv (\lambda_u/\lambda_d)^2. \tag{1}$$

The reader will notice that we abbreviate particle yields, *e.g.*, $Y_{\pi^\pm}$ by particle name $\pi^\pm$.

Using SHARE, we evaluate for a set of statistical parameters the particle yields and as appropriate, ratios, and then find in least square minimization process the best parameter for the experimental results applicable to the considered collision system. We use here the most central event trigger available (5%). For the top energy at AGS, we adopt nearly the totality of the experimental results considered by prior authors as stated in Ref. [18], listed here and comprising the following further developments:

i) Another way to introduce fugacity $\lambda_{\rm I}$ is to conserve electric charge, see [18]. Thus $d > u$ asymmetry is equivalent to the requirement that the total charge $Q$ of the hadronic fireball is a fixed fraction $f = 0.391$ of the total baryon number $B - \overline{B} = 363 \pm 10$ (1) (*we point out and count the number of measurements by having behind each value used in parenthesis a sequential number*), established by proton and neutron content of the colliding gold ions, *i.e.*, $Q = 142 \pm 5$ (2). We note that these values arise from our choice of the centrality trigger condition see, *e.g.*, table I, in Ref. [26].

ii) We adopt a slightly different strategy in use the available particle yield data, in order to limit the influence of the systematic error on the fit result: rather than to fit $K^- = 3.76 \pm 0.47$ yield, we fit $\mathrm{K}^+/\mathrm{K}^- = 6.32 \pm 0.65$ (3) which is seen in Fig. 6 of Ref. [26].

iii) We explore what happens when we include in the fit the (redundant) but independently measured precise ratio $\mathrm{K}^+/\pi^+ = 0.197 \pm 0.013$ (4) (value taken from conclusions to Ref.[27]) , which compares to the implied ratio $\mathrm{K}^+/\pi^+ = 0.177 \pm 0.037$ derived from the individual yields we use: $\mathrm{K}^+ = 23.7 \pm 2.86$ (5) (from table I in Ref. [26], including systematic error), and $\pi^+ = 133.7 \pm 9.93$ (6) (from extrapolation of Ref. [28] as used in [18]) The results we present are obtained including this as an independent measurement. Removing this ratio yields a reduction of P-value from, *e.g.*, 65% to 55% but does not affect materially the results we discuss.

iv) The other particle yield or, respectively, ratio values we use are: $\Lambda = 18.1 \pm 1.9$ (7) , $\overline{\Lambda} = 0.017 \pm 0.005$ (8), and $p/\pi^+ = 1.23 \pm 0.13$ (9), in all of these following the procedure of Ref.[18]. One of the reasons we did not deviate wherever possible from the data set of Ref.[18] was to assure that the results we obtain can be compared directly with earlier work.

v) We further study the influence of the recently published E917 ratio $\phi/\mathrm{K}^+ = 0.03 \pm 0.006$ [29], obtained within and interval of $\delta y = \pm 0.4$ units of rapidity around the mid-rapidity. We choose from the other measurements presented ($\phi$ yield, $\phi/\pi$) this result as it is the most precise one, and suitable to a qualitative extrapolation to a total yield ratio. We assume that the Gaussian shape rapidity distribution has $\sigma_\phi = 0.8$ which is consistent with the data shown by E917 [29], and the energy dependence systematics of $\sigma_\phi$ obtained by the NA49 collaboration, see Fig. 3 in [30]. Since the interval of $|\delta y| = 0.4 < \sigma_\phi = 0.8$ and $\sigma_\phi = 0.8 \lesssim \sigma_{K^+} = 0.96 \pm 0.6$ ($\sigma_{K^+}$ is from Ref. [26]), to %-precision, the relation of yields within the rapidity interval to the $4\pi$ total yield is

$$\left.\frac{\phi}{\mathrm{K}^+}\right|_{4\pi} \simeq \frac{\sigma_\phi}{\sigma_{\mathrm{K}}} \left.\frac{\phi}{\mathrm{K}^+}\right|_{y\in(-0.4,+0.4)}. \tag{2}$$

Thus, we adopt as the $4\pi$ ratio $\phi/\mathrm{K}^+|_{4\pi} = 0.025 \pm 0.006$ (10), which expresses the fact that the $\phi$ is expected to have a narrower rapidity distribution than the $\mathrm{K}^+$.

The SH model comprises aside of the already mentioned 5 parameters $T$, $\mu_{\rm B}$ (equivalently valance light quark fugacity $\lambda_q$), $\gamma_s$, $\gamma_q$, $\lambda_I$ also the fireball volume $V$ and $\lambda_s$, the strange quark fugacity. In principle this last parameter can be fixed by the requirement that the strangeness and anti-strangeness content balances in the fireball, *i.e.*, within the grand-canonical ensemble,

$$\langle s \rangle = \langle \bar{s} \rangle. \tag{3}$$

However, we hesitate to use this constraint since:

a) When chemical analysis includes both $\gamma_s, \gamma_q$ and one of the sides of above equation involves in essence just one particle species ($\mathrm{K}^+$ here) this constraint has in general several possible solutions.

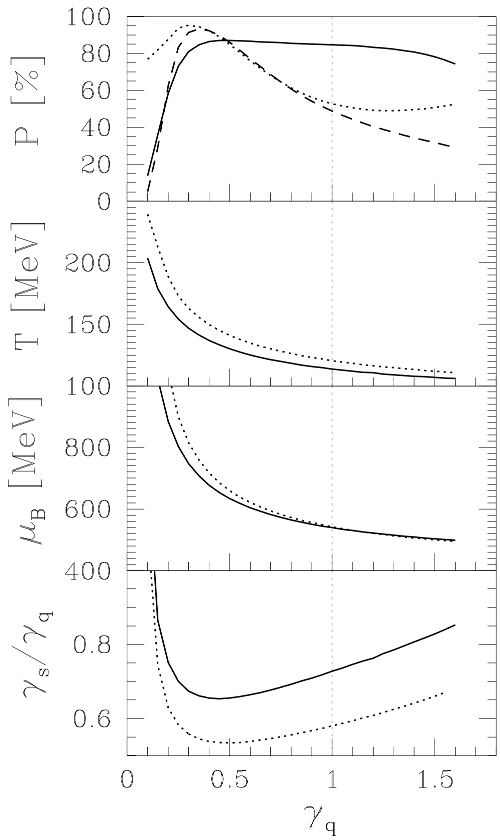


FIG. 1: From top to bottom: statistical significance of the fit for the data set, see text, at a fixed value of $\gamma_q$; chemical freeze-out temperature $T$; baryochemical potential $\mu_{\rm B}$; strangeness phase space occupancy divided by light quark occupancy $\gamma_s/\gamma_q$, all as function of the prescribed to the fit light quark phase space occupancy $\gamma_q$. Dashed line in upper section includes in fit the $\phi$. Dotted lines are obtained imposing strangeness conservation. Vertical line, at $\gamma_q = 1$, is for orientation only.

b) In the condition Eq. (3), all the other measurements combine predicting the yield of $\mathrm{K}^+$ required by the strangeness balance. This results in a consistency test of the data sets obtained from several experiments employing different instruments.

All this speaks against implementing this constraint and the results we present were obtained not enforcing Eq. (3). We will show by how much this constraint could be violated (in relative terms about 10%) and also show that its enforcement is not in essence altering the results shown.

In this study, we have 7 free parameters and up to 10 data points, of which one comprises partial redundancy. We will validate the fit instead of $\chi^2$ by the associated significance level $P$[%] which is obtained in SHARE using the CERN library "PROB" procedure [31]. $P$[%] is a function of the number of parameters $p$, and measurement points $r$. When these numbers are small, and in particular, the number of measurements is not much greater than the number of parameters, the value of total $\chi^2$ must be much smaller than what is usually expected for the 90% significance level result ($\chi^2 \simeq p - r$). Using this tool we find that 'good looking' figures arise for $P \simeq 15\%$ applicable to the result shown in Ref. [18]. Such a low significance level could be result of chance, but more likely it means that either the error on some of the measurements considered is in realty bigger, or the theoretical model needs further refinement, such as, *e.g.*, light quark chemical non-equilibrium.

In view of the above, we first wish to understand if the $\gamma_q = 1$ choice (light quark chemical equilibrium) is compelling. Using the SHARE1.2 package (without particle widths), we obtained the significance level ($P$-value) of our fits which we show in the top section of Fig. 1. We see (solid line) the significance level of our SHARE fit with 9 first experimental results, which has a plateau near 80% in the range $0.3 < \gamma_q < 1.5$. Eliminating the one redundant data point the significance level drops to 55% and the range of acceptable values of $\gamma_q$ widens further. The vertical line, in Fig. 1, is placed at the chemical equilibrium, with assumed value $\gamma_q = 1$.

The dashed line, in the top panel of Fig. 1, represents the significance level arising when the new 10th experimental point $\phi/\mathrm{K}^+$ is included in the analysis. The best fit is pushed well below chemical equilibrium with $\gamma_q \simeq 0.4$, and the significance level rises nearly to 90%. As this result shows, there is no compelling reason to consider only the case of light quark chemical equilibrium. Indeed this added experimental result favors chemical non-equilibrium for light quarks. The full chemical equilibrium $\gamma_s = 1, \gamma_q = 1$ appears inconsistent with the data set as can be seen inspecting the bottom panel of Fig. 1 where the ratio $\gamma_s/\gamma_q$ is presented.

Dotted lines, in Fig. 1, were obtained enforcing strangeness conservation condition, Eq. (3), as was done in Ref. [18]. This condition does not influence in essence the discussion we present though in detail minor differences arise. The two strategies we pursued in finding the best fits assure us that we have obtained the best fit in a situation involving many parameters, where several local minimal points are present. Our analysis shows that the suggestion that at low reaction energies the freeze-out of hadrons occurs well below the theoretical phase boundary between QGP and HG is not fully justified, as it is result of the assumption of chemical equilibrium.

Specifically, we find for the best fit with $\phi/\mathrm{K}^+$ a hadronization temperature $T = 142 \pm 3$ MeV and the baryochemical potential $\mu_{\rm B} = 708 \pm 60$ MeV. We realize that both these values $T$ and $\mu_{\rm B}$ appear at first sight to be beyond the phase boundary region of the hadron gas, in the deconfined domain, given the estimate for the critical boundary [32], and the related development of the liquid QGP phase model [33]. However, one has to realize that the relatively small values for $\gamma_q$ and $\gamma_s$ we obtained imply a significant reduction in the equilibrium QGP pressure, which pushes up the temperature of the non-equilibrium phase boundary. This opens the ques-

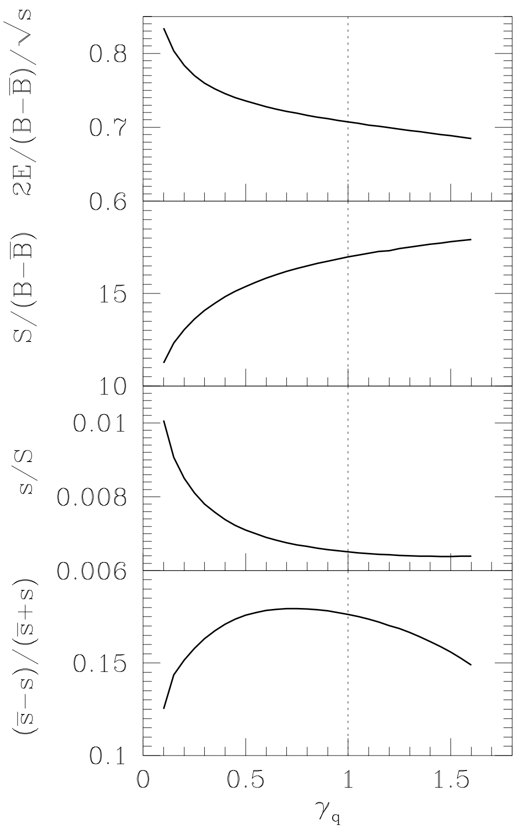


FIG. 2: Physical properties of the thermal fireball at chemical breakup as function of $\gamma_q$. From top to bottom: thermal energy content weighted with $\sqrt{s_{\rm NN}} = 2.4$ GeV; entropy per baryon $S/(B-\bar{B})$, strangeness per baryon $s/(B-\bar{B})$ and the strangeness asymmetry of the fit, $(\bar{s}-s)/(\bar{s}+s)$.

tion if indeed the hadron yield results seen at AGS are not the product of the breakup of a deconfined state. In our earlier study of light ion collisions at AGS, we had noticed that the results allowed interpretation in terms of both confined and deconfined baryon rich fireball formation [34].

We can only speculate about the physical reasons behind these small values of favored phase space occupancies: $\gamma_q = 0.35 \pm 0.27$, $\gamma_s = 0.23 \pm 0.18$. For example, if the deconfined state were to be well characterized at high baryon density by effective heavy quarks, with $m \simeq 350$ MeV, these quark equilibrium yields after hadronization at $T = 142$ MeV could well appear much below chemical equilibrium. This is consistent with the low value of entropy per baryon, Fig. 2, $S/(B-\bar{B}) = 14 \pm 2$. This situation is opposite to what happens for the small baryon density case (RHIC), with effectively small quark masses at hadronization, where the hadronization process overpopulates the hadron yield.

Considering together the AGS, SPS and RHIC energy ranges, we recognize that the hadronization temperature arises from a combination of several effects: the location of the equilibrium critical curve in the $T, \mu_{\rm B}$-plane, shift in the critical curve due to chemical non-equilibrium conditions, and supercooling due to dynamics of the expanding fireball. The last effect is particularly significant at RHIC while the first is probably most relevant at AGS as we noted above. At RHIC, the fast transverse expansion is seen in many observables, and it is generally believed that a new partonic phase has been created. For an equilibrium system the phase cross-over would be expected at $T = 164 \pm 10$ MeV [32]. However, the wind of colored particles expanding against the color-non-conducting vacuum can go on until the sudden breakup near to $T = 140\,$MeV [9, 15]. Aside of theoretical arguments, and fit results, such low hadronization temperatures are consistent with the observed resonance yield, for $K^*, \phi$ [35], as well as $\rho^0, f_0$ and $\Lambda(1520)$ [36].

Returning to the discussion of the physical properties of the fireball: aside of entropy per baryon mentioned above, we obtain other relevant physical properties of the source of produced hadrons using the statistical parameters to evaluate the phase space properties. We present, in Fig. 2 from top to bottom, the thermal energy per baryons as fraction of the center of momentum energy available in the reaction, the single particle entropy per baryon, strangeness per baryon and the strangeness asymmetry in the fits we consider when strangeness conservation is not enforced. For the interesting range $\gamma_q \simeq 0.4$, the value $s/S \simeq 0.008 \pm 0.001$ is significantly below the SPS and RHIC level [4]. This is consistent with the notion that strangeness yield rises with energy faster than light quark yield, as can be argued considering the mass–energy threshold for the production of these flavors, and the time available in the collision.

Considering that one measurement ($\phi$/K$^+$) pushes the discussion of AGS results toward a breakup of a deconfined state, we wish to understand if other measurements could confirm and solidify this result. We present, in Figs. 3 and 4, the variation of hadron ratios as function of $\gamma_q$ with other relevant statistical parameters varying as indicated in Fig. 1. We see considerable sensitivity of hadron ratios considered to the value of $\gamma_q$. We place the $\phi$/K$^+$ experimental result in the top panel of Fig. 3 at an appropriate value of $\gamma_q$, indicating with dotted lines the range of $\gamma_q$ consistent with the measurement error. Availability of other strange hadron ratios would provide the consistency check required to confirm that $\gamma_q < 1$.

The results, presented in Figs. 3 and 4, suggest which of the experimental ratios are of relevance in the study of chemical non-equilibrium. We see that some vary strongly, and that others vary little, *e.g.*, $\Lambda/p$ ratio is flat to within 10% in the entire range of $\gamma_q$ considered. Clearly, experiments will have great difficulty to reach precision at %-level to see such variation. We considered also baryon to meson ratios involving $\Xi$, $\Lambda$ with K (and antiparticles) Mostly, these turned out to be very insensitive, *i.e.*, flat to within 10%. The exception are ratios of $\overline{\Lambda}/K$ which are flat only for $\gamma_q > 0.4$. The variability

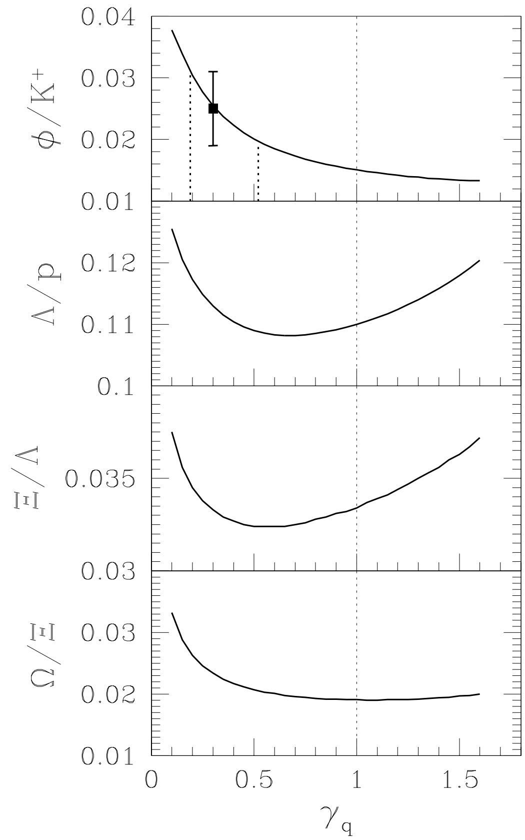


FIG. 3: From top to bottom: relative yields of $\phi/\mathrm{K}^+$, $\Lambda/p$, $\Xi^-/\Lambda$ and $\Omega/\Xi^-$ as function of $\gamma_q$. The experimental yield $\phi/\mathrm{K}^+$ is placed at best value of $\gamma_q$ and the range (1 s.d.) of possible $\gamma_q$ is indicated by vertical dots.

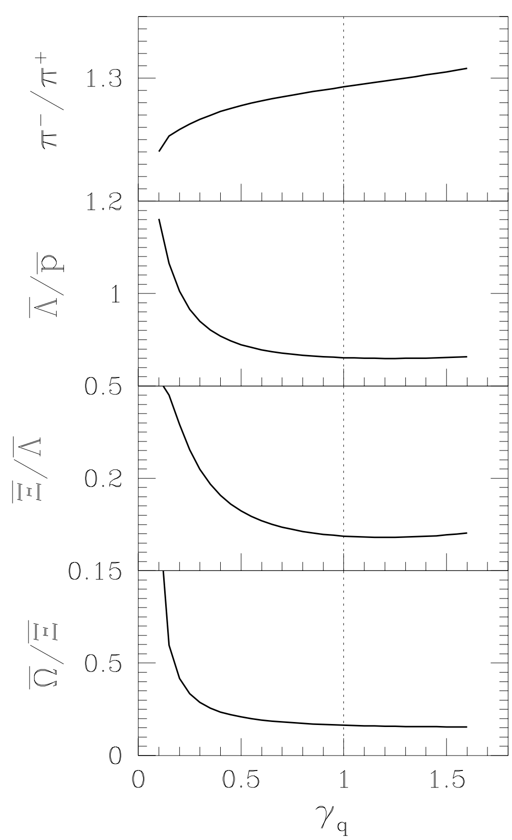


FIG. 4: From top to bottom: relative yields of $\pi^-/\pi^+$, $\overline{\Lambda}/\bar{p}$, $\overline{\Xi^-}/\overline{\Lambda}$ and $\overline{\Omega}/\overline{\Xi^-}$, as function of $\gamma_q$.

for small $\gamma_q$ is accounted for in the ratios shown in Fig. 4 involving $\overline{\Lambda}$.

We note that the ratio of $\overline{\Lambda}/\bar{p} \lesssim 1$ at $\gamma_q < 0.2$. The value of this ratio has been of considerable interest [37]. The experimental result $\overline{\Lambda}/\bar{p} = 3.6^{+4.7+2.7}_{-1.8-1.1}$ favors a small value of $\gamma_q$ We further note that the ratio $\pi^-/\pi^+$, seen in Fig.4, is consistent with the result $\pi^-/\pi^+ = 1.23 \pm 0.02 \pm 15$–$20\%$ obtained in central collisions [38], and again a small value of $\gamma_q$ is favored when comparing the experimental result to the SH model prediction, obtained fitting other experimental data.

This discussion confirms the importance of multi-strange hadrons and strange antibaryons as a valuable hadronic signature. In this context, it is important to understand the overall strangeness yield. Evaluating the number of valance strange quark pairs per baryon in terms of the parameters characterizing the phase space, we obtain for the entire relevant range:

$$\frac{\bar{s}}{(B-\overline{B})} = 0.12 \pm 0.02 \pm 15\%,\ 0.2 < \gamma_q < 1. \quad (4)$$

We show above the yield of $\bar{s}$ in emitted hadrons, since is greater than that of $s$ in our study. When we enforce strangeness conservation Eq. (3), the presented result is reproduced. The first error stated in Eq. (4) is the variability of the yield as function of diverse parameters. We see that it is well below the estimate of the propagation of the experimental errors into the theoretical yield, which we present second as the estimated error. We note that ratio Eq. (4) includes aside of open strangeness, also a noticeable contribution contained in $s\bar{s}$ mesons ($\phi$ and components in $\eta,\ \eta'$).

We see, in Fig. 2, that there are more $\bar{s}$-hadrons emitted than $s$-hadrons. If this $\bar{s} > s$ asymmetry were to be confirmed by more experimental data, this could be explained by strangeness distillation phenomenon expected to occur at AGS energy [39]. After the excess of $\bar{s}$ is evaporated, the residue is a quark soup enriched with $s$-quarks, a strangelett, which when metastable, may have escaped observation.

For central collisions, at the top AGS energy, the transverse slopes of particle spectra $T_\perp \simeq 200$ MeV (*e.g.*, K-spectra, see Ref. [27]). This result leads to the average radial expansion of the AGS fireball at $\langle v_\mathrm{r}\rangle = 0.5$c [40]. Such a high speed of radial expansion is, for us, hard to understand. On the other hand, for a single freeze-out at $T = 143$ MeV we report here, we estimate the required $\langle v_\mathrm{r}\rangle = 0.2$–$0.3$c (note that results of analysis [40] do not

fully apply as these were done assuming chemical equilibrium yields of resonances). The introduction of chemical non-equilibrium and the associated high chemical freeze-out temperature harbors the potential for consistent understanding of particle spectra and yields, also within a kinetic reaction model [41].

In conclusion, we have presented a comprehensive and systematic study of the experimentally measured particle yield ratios obtained in $\sqrt{s_{NN}} = 4.8$ Au–Au collisions (11.6 GeV/c Au on fixed target). We have analyzed the chemical freeze-out conditions allowing the QGP associated chemical non-equilibrium. We have found that the present data sample is not sufficient to argue decisively for or against the QGP presence at AGS energy scale. However, consideration of the recently measured yields of $\phi$, the $\pi^-/\pi^+$ along with indirectly evaluated $\overline{\Lambda}/\bar{p}$ favors as the result of the data analysis the chemical non-equilibrium hadronization at the phase boundary between the confined and deconfined baryon rich phase. The results we presented indicate that exploration of the phase transition between baryon rich confined and deconfined phases may be possible by means of relativistic heavy ion beams in the energy range of 10 $A$ GeV/c.

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